NASA Technical Memorandum 86377

IMPROVING ENGINEERING SYSTEM DESIGN BY FORMAL DECOMPOSITION, SENSITIVITY ANALYSIS, AND OPTIMIZATION

(NASA-TM-86377) IMPROVING ENGINEERING SYSTEM DESIGN BY FORMAL DECOMPOSITION, SENSITIVITY ANALYSIS, AND OPTIMIZATION (NASA) 10 p HC A02/MF A01 CSCL 12B

N85-19765

Unclas
G3/66 14367

J. Sobieszczanski-Sobieski and J.-F. Barthelemy

FEBRUARY 1985

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23665

IMPROVING ENGINEERING SYSTEM DESIGN BY FORMAL DECOMPOSITION, SENSITIVITY ANALYSIS, AND OPTIMIZATION

J. SOBIESZCZANSKI-SOBIESKI
J.-F. BARTHELEMY

SUMMARY

A method for use in the design of a complex engineering system by decomposing the problem into a set of smaller subproblems is presented. Coupling of the subproblems is preserved by means of the sensitivity derivatives of the subproblem solution to the inputs received from the system. The method allows to divide work among many people and computers.

INHALTSANGABE

Es wird vorgestellt, ein komplettes Engineering System zu entwickeln, das man in kleinere Untersysteme zerlegen kann. Das Zusammenlegen von Unterproblemen kann erreicht werden mittels der Verfeinerungen der Ableitungen von Unterproblemen, zu loesen empfangen durch Eingaben welche vom System werden. Die Methode teilt die Arbeit unter vielen Leuten und unter vielen Rechnern auf.

INTRODUCTION

Engineering systems are frequently composed of subsystems which are mutually coupled so that a modification in one affects the others and ultimately influences the performance of the whole. Designers of such systems are confronted with a closed loop situation whereby the decision making at the system level requires information about the subsystems that have not yet been designed and vice versa. The iterative approach commonly used to break the deadlock relies on past experience, judgment, and intuition as substitutes for the unavailable information and becomes increasingly inadequate as the systems grow in complexity and advance far away from the experience base.

The paper outlines a method for improving the iterative design of complex systems by making it more systematic and based on a set of coherent mathematical concepts. While rooted in mathematics, the approach deliberately avoids handing over the entire design process to the computer. On the contrary, the emphasis is on a broad work front of people and computers to combine the computer efficiency with the human intelligence indispensable in design.

DECOMPOSITION

The key to the proposed approach is a formalized decomposition of the large design problem into a set of smaller manageable subproblems coupled by means of the sensitivity data that measure the change of the subsystem design due to a change in the system design. Let ES be an engineering system composed of the subsystems SS_1, SS_2,...SS_i...SS_n as shown in Fig.1 (the abbreviations are defined in Table 1, and Table 2 gives examples for the generic quantities in the context of aircraft design). The design variables are grouped in a vector SV for ES and the vectors DV_i for SS_i. The ES has a performance index PS that should be maximized within the system constraints collected in a vector GS. The ES imposes demands on each SS_i. These demands are quantified by entries of a vector DS_i which depends on SV through analysis of ES. Suppose that each SS_i is designed by manipulating DV_i so that it meets its DS_i, regarded as constants, while maximizing its safety margin SM_i representing a set of subsystem constraints GSS_i. These tasks separate for each SS_i can be carried out concurrently by whatever means the SS_i designers choose, including the appropriate analysis, optimization, and, also, judgment and experimentation.

A new element required under the proposed approach is evaluation of the sensitivity of the maximum (optimum) SM_i to changes in DS_i in form of the optimum sensitivity derivatives $\partial SM_i/\partial DS_i$. At the ES level, these derivatives combined with the derivatives $\partial DS_i/\partial SV$ in chain differentiation yield the sensitivity of SM_i to changes in SV in form of derivatives $\partial SM_i/\partial SV$. The maximum SM_i and its derivatives show the ES

designer, with a linear extrapolation accuracy, how the change of SV that he controls will affect the SM_i for each SS_i. Guided by this information and by the ES analysis, the ES designer can decide which variables in SV to change and by how much in order to move toward the goal of making all the constraints GS and GS_i satisfied while maximizing the PS. The SV change will alter the DS_i. Responding to that, the SS_i designers modify their designs and pass updated information to the ES designer who, then, changes the SV again, and so on. In this manner the ES and the SS_i designers carry on a systematic iteration toward the improved system design, trading the data precisely defined in form of the DS_i, SM_i, and their derivatives. Each designer works on a separate assignment with the control of PS vested in the ES designer while the SS_i designers focus on their SS_i feasibility. The whole problem is decomposed yet remains coupled by the ES-SS_i data exchange shown in Fig.1.

OVERALL PROCEDURE

Based on the above qualitative description, one may now formulate a step-by-step procedure to implement the decomposition approach.

STEP 1. Initialize the system.

STEP 2. Analyze the system. Calculate PS, GS, DS_i, and $\partial DS_i/\partial SV$.

STEP 3. Design subsystems SS_i. The DV_i are manipulated within the upper and lower bounds, L_i and U_i, so as to find maximum SM_i for given DS_i. The latter requires vector of equality constraints GE_i for those DS_i that are also functions of DV_i. These constraints enforce equality of the DS_i values prescribed at the system level and computed as a function of DV_i so that $GE_i = DS_i(SV) - DS_i(DV_i) = 0$. Formally, the task may be formulated as an optimization

$$\max_{DV_i} SM_i(DV_i, DS_i) \quad \text{subject to constraints} \qquad (1)$$

$$GE_i(DV_i, DS_i) = 0. \quad L_i \le DV_i \le U_i$$

The output of the operation is: $\overline{SM_i}=(SM_i)_{max}$, and the optimal subsystem design variables, $\overline{DV_i}$

STEP 4. Analyze each SS_i design for sensitivity to the inputs received from the system to obtain the $\partial SM_i/\partial DS_i$.

STEP 5. Modify the SV to improve the system design. In this operation, one uses the $\partial DS_i/\partial SV$, SM_i, and $\partial SM_i/\partial DS_i$ obtained in STEP 2, 3, and 4, to extrapolate each SM_i as a function of the increment ΔV

$$SM_i(\Delta SV) = SM_i + \frac{\partial SM_i}{\partial DS_i}\frac{\partial DS_i}{\partial SV}\Delta SV \tag{2}$$

Improvement of the system design may be formalized as an optimization:

$$\text{a) } \max_{SV} PS(SV) \quad \text{subject to constraints} \tag{3}$$

$$\text{b) } GS(SV) \leq 0, \text{ c) } SM_i(SV) \leq 0 \text{ (for all i)}$$

$$\text{d) } L \leq SV \leq U$$

in which the system level analysis provides the PS and GS, and the SM_i in eq.3c is approximated by eq.2. The bounds in eq.3d include "move limits" protecting the accuracy of the extrapolation in eq.3c. The above optimization problem may have no feasible solution within the move limits in eq.3d, if it begins with significant constraint violations in eq.3b and c. If a feasible solution can not be found, an acceptable outcome of eq.3 is a new design point moved as close to the constraint boundary as possible. The result of this step is a new SV defining a modified design of the system.

STEP 6. Repeat from STEP 2 until all the constraints GS are satisfied, all safety margins SM_i are non-negative, and the performance index PS has converged.

In the above procedure, also shown in Fig.2, the analyses in STEP 1 and 2 are problem-dependent. The behavior sensitivity analysis required to obtain the $\partial DS_i/\partial SV$ can be obtained by either a finite difference technique or, preferably, by a quasi-analytical method, e.g.,[1]. The optimizations defined by eq.1 and 3 can be carried out by any suitable algorithm capable to search an n-dimensional constrained design space,

e.g.,[2], although the use of a formal optimization method is a recommendation rather than a requirement. The optimum sensitivity derivatives in STEP 4 can be calculated by means of the algorithms described in [3],[4],[5],[6]. Extension of the above two-level algorithm to multilevel systems is given in [7], and its application to aerospace systems is discussed in [8].

Initial tests including two-level [9] and three-level [10] structural optimizations showed satisfactory comparisons with the results obtained without decomposition. A status report on a multidisciplinary test case is documented in [11]. It involves redesign of a wide-body transport aircraft wing for improved fuel consumption for a prescribed mission under constraints imposed by strength, aerodynamics, and aircraft performance requirements. Fig.3 shows the aircraft and a three-level decomposition scheme devised for the problem. Research and development continue to learn more about the algorithm's convergence properties, sensitivity to the extrapolation errors and lack of synchronization among the subtasks, ability to handle direct couplings among the SS_i's, ability to adjust to discrete or judgmental decisions, and computer hardware dependence.

SUMMARY AND CONCLUDING REMARKS

The paper has presented a method for decomposing a large engineering design problem into a set of smaller subproblems. Each subproblem is self-contained so that all the subproblems can be worked on concurrently and a broad work front of people and computers can be developed. The method's testing to date has been satisfactory according to the references cited. Further development of the method is focused on the algorithmic details and continuing test applications in aerospace design. The development entails also the issues of the data management and utilization of parallel computation capabilities being offered by modern computer technology.

REFERENCES

[1] Adelman, H.M., and Haftka, R.T.: Sensitivity Analysis for Discrete Structural Systems - A Survey; NASA TM 86333, 1984.

[2] Vanderplaats, G.N.: Numerical Optimization Techniques for Engineering Design: with Applications; McGraw-Hill Book Co., 1984.

[3] Sobieszczanski-Sobieski, J., Barthelemy, J.F., and Riley, K.M.: Sensitivity of Optimum Solutions to Problem Parameters; AIAA J., 9, 1982, 1291-1299.

[4] Barthelemy, J.F., and Sobieszczanski-Sobieski, J.: Optimum Sensitivity Derivatives of Objective Functions in Nonlinear Programming; AIAA J., 6, 1983, 913-915.

[5] Fiacco, A.V.: Introduction to Sensitivity and Stability Analysis in Nonlinear Programming; Academic Press, 1983.

[6] Vanderplaats, G.N..: Efficient Calculation of Optimum Design Sensitivity; AIAA Paper No 84-0855-CP.

[7] Sobieszczanski-Sobieski, J.: A Linear Decomposition Method for Large Optimization Problems; NASA TM 83248, 1982.

[8] Sobieszczanski-Sobieski, J., Barthelemy, J.F., and Giles, G.L.: Aerospace Engineering Design by Systematic Decomposition and Multilevel Optimization; Int. Council of the Aeronautical Sc., 14th Congress, Paper No ICAS-84- 4.7.3.

[9] Sobieszczanski-Sobieski, J., James, B., and Dovi, A.: Structural Optimization by Multilevel Decomposition; AIAA Paper No 83-0832-CP, 1983.

[10] Sobieszczanski-Sobieski, J., James, B., and Riley, M.F.: Structural Optimization by Generalized, Multilevel Decomposition; AIAA Paper No 85-697-CP.

[11] Wrenn, G.A., Dovi, A.R., Barthelemy, J.F., and Radovcich, N.A.: Multilevel, Multidisciplinary Optimization Scheme for Sizing a Transport Aircraft Wing; AIAA Paper No 85-0803-CP.

ADDRESS OF THE AUTHORS

Jaroslaw Sobieski
Interdisciplinary Research Office, MS-246
NASA Langley Research Center
Hampton, Virginia 23665 USA

Jean-Francois Barthelemy
Virginia Polytechnic Institute and State University
C/O Interdisciplinary Research Office
(as above)

Table 1 Summary of Generic Terms.

DS_i	- vector of demand quantities imposed by the system on subsystem i.
DV_i	- vector of design variables for subsystem i.
ES	- (engineering) system.
GE_i	- vector of equality constraints for subsystem i.
GS	- vector of system inequality constraints; an inequality constraint is defined as g=(DEMAND/CAPACITY)-1, satisfied when $g \leq 0$.
GSS_i	- vector of inequality constraints for subsystem i.
L, L_i	- vector of lower limits on SV, and DV_i, respectively (move limits included).
PS	- performance index for ES (a scalar).
SM_i	- safety margin for SS_i (a scalar), defined as SM_i=max(CAPACITY/DEMAND)-1, or in terms of a set of g's (see GS): SM_i=max(-g/(g+1)) .
SS_i	- subsystem i.
SV	- vector of system design variables.
U, U	- vector of upper limits on SV, and DV , respectively (move limits included)

Table 2 Examples of the Equivalents of the Generic Terms Typical for an Aircraft Application.

DS_i	- at the middle level: lift required of the wing; at the bottom level: edge loads N_x, N_y, N_{xy} on a wing cover panel.
DV_i	- at the middle level: wing bending stiffness distribution; at the bottom level: detailed wing panel dimensions.
ES	- aircraft, top (system) level;
GE_i	- at the middle level: wing structure weight prescribed at the top level; at the bottom level: panel spanwise membrane stiffness prescribed at the middle level.
GS	- runway length.
GSS_i	- at the middle level: wing tip deflection; at the bottom level: panel local buckling.
PS	- fuel economy for a given mission.
SS_i	- the wing box, middle level; the wing cover stiffened panels, third (bottom) level.
SV	- wing structural weight and airfoil thickness to chord ratio.
$\partial DS_i/\partial SV$	- derivative of wing lift with respect to structural weight.
$\partial SM_i/\partial DS_i$	- derivative of wing panel safety margin with respect to edge loads.

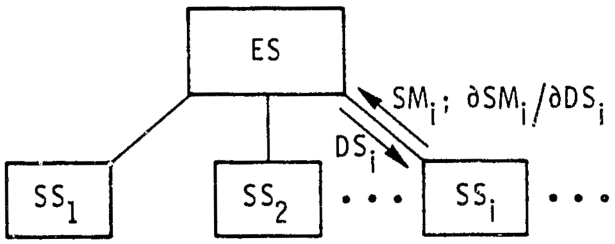

Figure 1 Typical two-level system.

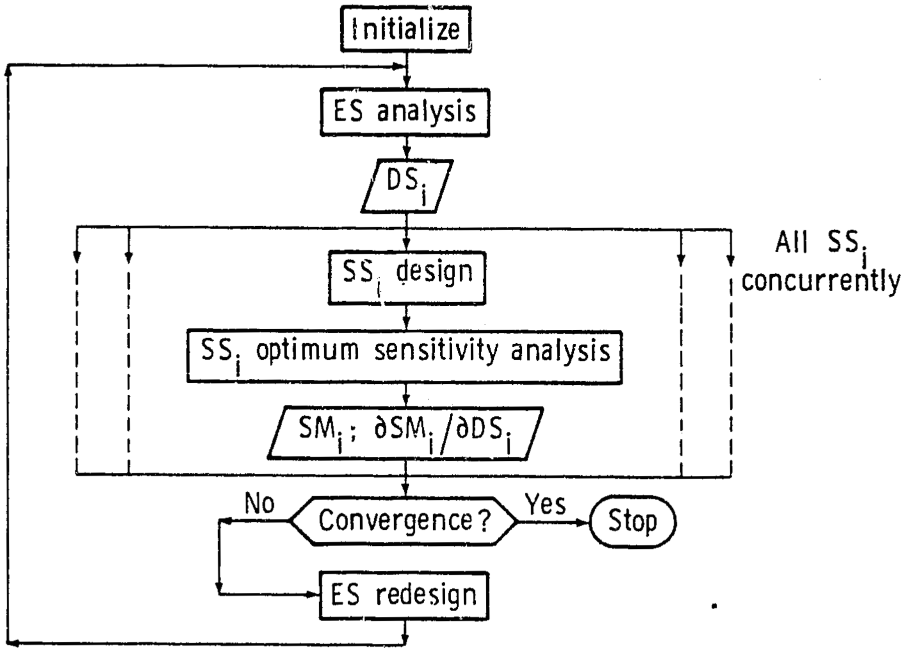

Figure 2 Two-level system optimization procedure.

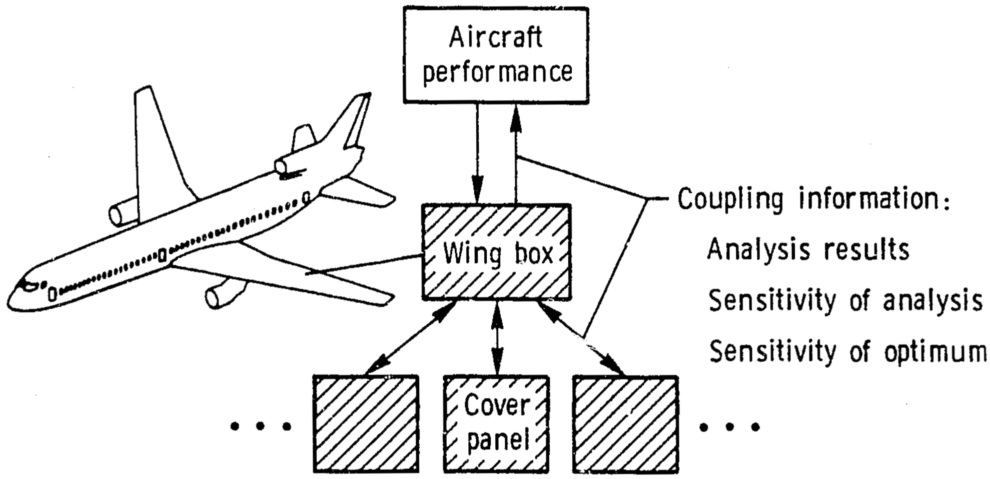

Figure 3 Decomposition for wing optimization.